Spring | 19

Boeing Insulation-Installation Group (BIG)

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It is more prevalent than ever for commercial aircraft to use tubing with tight-fitting insulation to carry hydraulic fluid, compressed air, and fuel. Designed with stable and lightweight construction for manual handling, our team has prototyped novel tooling for installing insulation onto complex aerospace tubing. Our design reduces ergonometric risk to operators, reduces processing time, and improves production capacity.

Project For Boeing Tubing Ducting and Reservoir Center

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Executive Summary

The Boeing Insulation-Installation Group (BIG) has been tasked with the challenge of finding a new method of installing insulation on titanium tubing used in a number of applications on Boeing aircraft. Currently, Boeing's Tube, Duct, and Reservoir Center (TDRC) installs the insulation on the tubing manually. This is a time-consuming and labor-intensive processes. It also presents a number of ergonomic issues for the installer. BIG, a team comprised of four senior mechanical engineering students at the University of Idaho, is using skills and knowledge gained during their undergraduate engineering curriculum to develop solutions to this challenging problem.

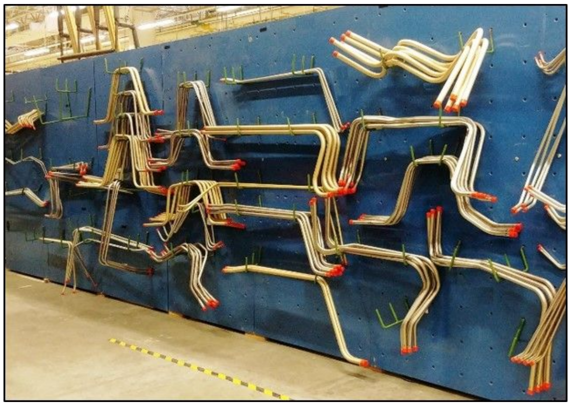
The BIG team first met with TDRC engineers and assessed the current installation method in order to clearly define the problem. BIG then brainstormed ideas, tested concepts, analyzed data, developed prototypes, and narrowed down the design path. This process led to the development of two viable design concepts that TDRC can pursue to address this ongoing manufacturing issue.

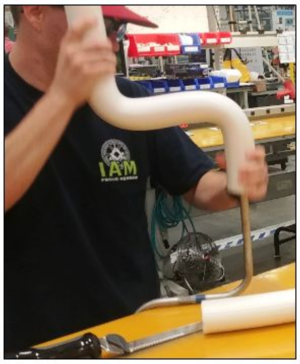
The two design concepts were (1) a powered device that pushes foam insulation over the titanium tubing; and (2) a powered tug that pulls the insulation over the tubing. These two concepts literally approached the problem from two directions. Each required design and fabrication of various components to produce a final assembly that was prototyped and tested.

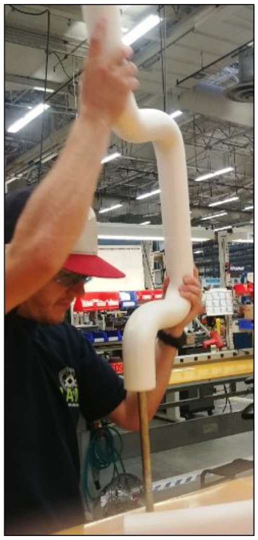
Both innovative concepts are potential solutions to TDRC's tubing insulation issue, and either could be perfected and incorporated into Boeing's manufacturing process. However, based on BIG's testing and evaluation of the two concepts, we recommend that the "Foam Pusher" be given greater consideration by TDRC because the Foam Pusher has the highest potential for a complete, low-cost, and reliable solution to the problem.

Background

Boeing Company's TDRC facility in Auburn, WA assembles, tests and prepares all tubing, ducting and reservoirs for The Boeing Company's commercial aircraft. One of the project design criteria included applying closed-cell insulation on to a pre-formed titanium tube. It is common for tubes to be bent into various geometries and configurations. The current installation procedure requires an operator to manually force insulation over the bent tubing without any sort of mechanical assistance. This can be time-consuming and can create ergonomic risks. The manual process is taxing on the operator who may complete dozens of these insulated tube assemblies per day. In addition, manual installation can result in damage to the tube and insulation, resulting in waste and rework.







Problem Definition

The Boeing Insulation-Installation Group (BIG) is tasked with the objective of introducing novel tooling and manufacturing processes to insulate tubing components for The Boeing Company. Goals include improving the overall ergonomics and efficiency of the manufacturing process currently orchestrated by The Boeing Company's Tubing, Ducting and Reservoir Center (TDRC).

Project Plan

The plan for the project included the following basic steps:

September/October 2018:

a. Introduction of the BIG team and the client and basic scoping of the project (Sep

b. Brainstorming session to develop a list of possible solutions.

c. Site visit to Boeing TDRC facility in Auburn, WA, to observe and assess current process and to discuss the problem with TDRC engineers.

d. Obtain samples of tubing and insulation materials for testing and evaluation.

November/December 2018:

e. Conduct baseline testing of current process.

f. Purchase materials to begin testing and prototyping.

January/February 2019:

g. Consult ergonomics experts on risks associated with current process.

h. Test and evaluate potential solutions and components.

i. Rule out non-viable solutions and begin focusing on leading design concepts.

March/April 2019:

j. Create engineering drawing package for prototype components and assemblies.

k. Fabricate prototype components and assemblies.

l. Conduct iterative testing and evaluation as the prototypes take shape.

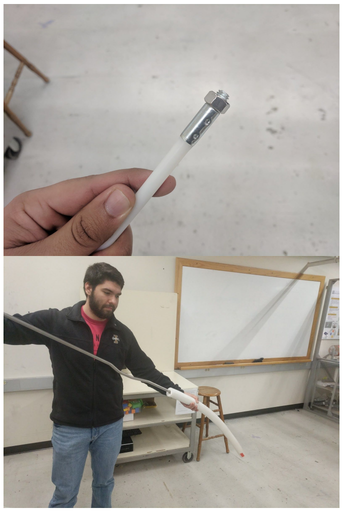
m. Conduct full-scale testing of final prototypes.

n. Demonstrate the prototypes for the client at their TDRC facility.

Concepts Considered

Several concepts were considered during this project:

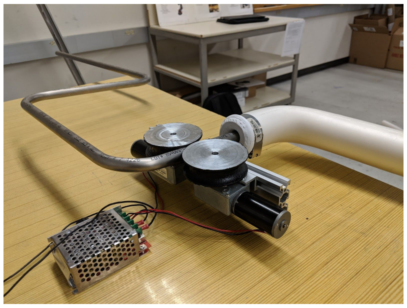
a. **Air bearing** – The air bearing concept involved forcing compressed air between the tubing and the insulation to create a layer of air that would act as a bearing that would reduce the coefficient of friction between the tubing and the insulation. This concept was rejected because the air flow would cause the insulation to shift and create pathways for compressed air to escape around the tubing. A complete air bearing was therefore not achievable at the principal friction points between the tubing and the insulation.

b. **Pipe puller** – The pipe puller concept involved the use of a flexible rod inserted through the insulation and tubing. The rod was then connected to the far end of the tubing and used to pull the tubing through the foam while the operator manually pushed the foam over the tubing. This procedure was only a partial solution and it still required the operation to apply a great deal of manual force to the tubing and insulation. The ergonomic risks of this concept were comparable to the current manufacturing process. However, this concept led to a better understanding of the dynamics of the interaction between foam and tubing. This in turn helped inspire the Foam Pusher concept.

c. **Finger trap** – The finger trap concept involved the use of a commercially available woven cable grip to grab to insulation and pull it over the tubing. This concepted was expected to provide a method of pulling the foam insulation without causing damage. However, based on preliminary component testing, the BIG team determined that the cable grip squeezed and constricted the foam insulation around the tubing, causing greater normal force and, therefore, greater friction between the insulation and the tubing. The finger trap did, however, provide a reliable method of gripping the insulation from the forward end without damaging it. See Appendix IV for more information.

d. **Bull nose** – The bull nose concept was developed based on observations of the way that the foam moved around the bends of the tubing. We noted that the flat face of the ends of the foam insulation resisted bending around the inside radius of the tubing bends. This created a sticking point in the process. The bull nose was designed as a smooth rounded cap that helped guide the front end of the insulation around the tubing bends. While the bull nose concept was effective, it did not produce a significant improvement in the installation process. See Appendix IV for more information.

Fabric sleeve – The fabric sleeve concept evolved from a desire to reduce the friction between the tubing and the foam insulation. The team tested the foam and the tubing to determine a baseline coefficient of friction. The team then tested the idea of inserting a fabric sleeve between the insulation and the tubing during installation and removing it when installation was complete. The sleeve successfully reduced the friction; however, it was difficult to retrieve and remove the sleeve from in between the tubing and the insulation after installation.

e. **Tug** – The tug concept involved the design and fabrication of a powered device that would grip the tubing with rollers and travel along the length of the tubing. As the tug moved along the tubing, it would pull the foam over the tubing. The pulling device rolls along the tube while pulling the insulation behind it as it goes. The rollers use a set of springs to keep pressure between them and the tube. The rollers also have a rubber coating to increase friction and keep from damaging the tube. They are shaped to contour the tube as well as possible. The rollers are each driven by a high torque geared motor. The motor roller assembly slides into the tube using a linear rail. This system keeps the assembly from binding when side loads are applied.



f. **Foam Pusher** – The foam pusher concept was developed in response to our observations of how the foam reacted when it was pulled over the tubing. The team observed that as the foam was pulled, it stretched and necked down. This necking down constricted the foam around the tubing and increased the normal forces between the foam and the tubing. This in turn increased the friction force resisting the installation process. The team observed during evaluation of the

pipe puller concept that by pushing the foam, it bunched up and expanded somewhat in radius. This had the opposite effect of pulling the foam and resulted in a reduction of the normal forces. Also, by pushing the foam, it was much easier to control the speed of advance of the foam over the tubing. By keeping the foam insulation in continuous motion over the foam, the concept took advantage of reduced friction forces by converting static friction to dynamic friction. To develop this concept, the team had to overcome the challenge of pushing the foam, a very flexible and compliant material, with sufficient force to drive it over the tubing. The team used a section of straight guide tubing to keep the foam straight and supported during the pushing process. A cup-shaped device was developed to uniformly apply pushing force to the back end of the foam section. The cup is pulled by a nylon strap and winch assembly guided by rollers to keep the pulling force aligned with the guide tube. Another challenge was developing a method of holding the tubing in place while the foam was pushed over it. The solution to this problem was to design a rubber “boat plug” or mandrel device that could grip the tubing from the inside with sufficient strength to oppose the force of the foam. Also, this mandrel had to be attached to the end of the guide tube. The foam pusher has been able to quickly and smoothly push the foam insulation over the tubing in a continuous motion and navigate the most difficult four-bend tubing configuration.

System Integration

Puller Design:

The pipe puller as described in part (b) of concepts considered is used in combination with both the tug (e) and the foam pusher (f). In the tug design the puller allows the operator to pull the insulation over the tubing from the back as the tug makes its way along the pipe at the front of the insulation. This is important because for a brief moment after the tug has rounded the corner of the tubing it is no longer pulling in the correct axis to move the foam along the tube. When the pipe puller is attached to the tube in the foam pusher design it allows the winch and cup to apply force to the insulation while keeping the tube stationary.

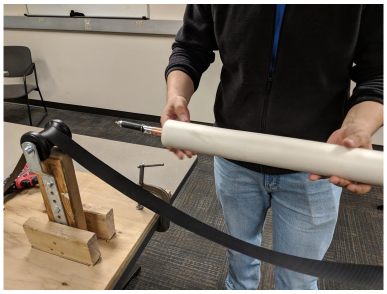
The tug also requires use of the bull nose (d) described in concepts considered. Its purpose is to attach a clamp to the insulation without constricting it and increasing friction. This clamp can then be connected to the tug device. This is what the tug uses to apply force to the insulation. It’s important that this connection is strong because of the large forces being applied by the tug. Used on its own, this piece could be made of plastic but as it goes around corners it will encounter significant forces. This means for the final design this will need to be made of metal.

Pusher Design:

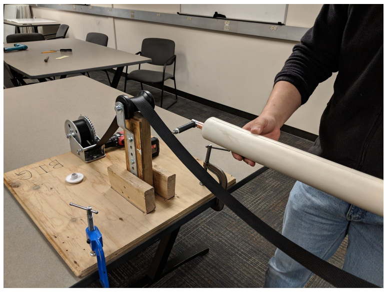
The foam pusher design is currently made primarily out of wood and secured to a workbench using C-clamps. For this design to be integrated into Boeing's manufacturing process the materials would need to be updated and a dedicated jig and table setup would need to be designed. The prime mover for the foam pusher is a handheld power drill. This power source is underpowered, making it prone to overheating and stopping. Also, the drill must be held and actuated by the operator, taking them away from assisting the insulation around the tubing. A more powerful motor, mounted to the device, with the ability to be operated using a foot pedal or other remote control should be implemented to replace the hand drill. The winch and strap for pulling the cup is not an optimal solution to this concept. With this design, many safety and mechanical issues are inherent. For example, the open gears on the winch can grab and pinch extremities and loose clothing when running. The same safety concerns are present where the strap rides over the roller. In addition, the strap is not reversible and must be repositions manually. A solution to these drawbacks is a rack and pinion driven design to push the cup back and forth along the guide pipe. The rack and pinion gears would have to be properly shrouded to protect the device and the operator.

The foam pusher can also be scaled for different tubing and insulation sizes quickly and easily. Our current design calls for the rubber mandril of the boat plug to be replaced with different sizes to fit the tubing. However, the cup would have to be modified to avoid being caught on the discontinuity created by the larger diameter tubing. A better solution might be to fabricate a boat plug assembly for each size of tubing. Different sized boat plug assemblies could be screwed or otherwise attached to the end of the guide pipe. Each assembly would have a fairing section integrated into the design to reduce the abrupt transition from the guide to the tubing.

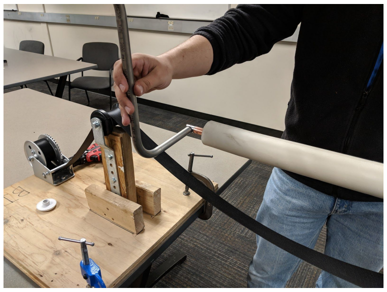
The steps to setup this device for operation are as follows:



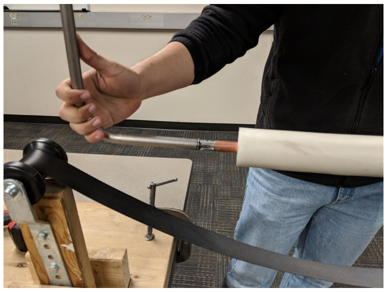
(1) Make sure the boat plug is straight and inline with the guide pipe. Then slide insulation over guide pipe.



(2) Release the compression in the boat plug by orienting it perpendicular with guide pipe.



(3) Slip the end of the tubing over the rubber mandrel of the boat plug until the tubing comes in contact with the washer.



(4) Reposition tubing and boat plug so that it is inline with the guide pipe.

(5) Use the device to push the insulation over the tubing.

Design Evaluation

Puller Design:

Appendix I is a DFMEA for the puller device. When creating the Design Failure Modes and Effects Analysis (DFMEA) for the puller design, we found that the greatest risks were related to the motors and potential pinch points. Because all of the motors being used are high torque it’s important that they are not powered on unintentionally. This could lead to something or someone getting caught in rollers or the winch mechanism. If the motors do get caught on something or bind up the motor controller may burn up. It is also possible in this case for the gearboxes on the motors to strip. Any one of these things will render the devices completely unusable. While a way to stop this has not been implemented in any of our current designs we would recommend adding some kind of current limiting circuit to the motor controller. Doing this would largely take care of these problems.

Another potential failure point is where the puller device applies force to the insulation. If there are any sharp contact points it could damage the insulation and the piece would need to be thrown out. To mitigate this for the pulling device, the insulation is attached at the end where it will be cut off.

To test the design a scale was used to verify that they would have enough pulling force. The time to install with the devices was also measured to make sure that it met the design requirements.

Because the puller design will never be manufactured on any significant scale the materials it is made of will not have any major environmental impact. That being said, the puller design is made of recyclable materials. However, this design may increase the amount of wasted material over the current method of installation because the damaged end of the insulation will need to be cut off after operation.

The steps to setup this device for operation are as follows:

1) Guide the rollers onto the end of the tube.
2) Slide the clamp onto the insulation and insert the bullnose
3) Secure the clamp around the bullnose
4) Apply power to the motors and pull the insulation over the tubing.

Below is a Design Validation Matrix for the puller device.

Device shall be multipurpose and be compatible with various bends	Use spring system with tensioner to allow for adjustment/fine tuning to determine if compatible with various tubes	Motor Housing, Rollers	02/27/2019	Success	Fine tune spring rates
Device shall be compatible with tubes of various lengths	Use 8020 railing to adjust for each type of tubing geometry to determine if compatible with various tubes	Motor Housing	02/27/2019	Success	Use square 8020 for weight reduction
All components shall have 95% reliability	Conduct fatigue analysis/FEA on components to predict service life of tool, look at spec sheets for statistics on reliablity if available	Full assembly	03/06/2019	Sucess	Final prototype omponents fabricated with robust materials for longevity
The system should be able to operate off a standard 120V wall outlet, or air.	Ensure system is compatible with wall outlet if necesarry	Full assembly	03/06/2019	Sucess	No need for powered or air equipment as current design
This project will be designed to operate in a controlled, indoor, and air conditioned environment.	Ensure system is will pose no risk to operators in vacinity	Full assembly	03/06/2019	Sucess	Systems fit indoors
Device shall insulate a tube in under three minutes	Test prototype and determine if time to assemble is satisfactory. Test multiple times to get an average installation time	Full assembly	04/03/2019	Success	Installation times are well within this time
Device shall reduce input from user	Compare ergonomic effects and implications of using tool and without using tool	Full assembly, operator	03/20/2019	Success	Devices significantly reduce user fatigue
This device should be user driven, staying in the constraints of the current working area.	Ensure that tooling fits within defined alloted area	Full assembly	03/20/2019	Success	Devices fit in workspace

Projected cost for production units shall be < $1500.	Ensure system costs less that requirement	Full assembly	04/03/2019	Sucess	Devices cost significantly less than defined limit
Cost of the first prototype shall not exceed $500.	Ensure system costs less that requirement	Full assembly	03/06/2019	Success	Devices cost significantly less than defined limit
Device shall maintain a consistent and uniform appearance	Test tool multiple times, observe effects on tubing and insulation, search for degredation or damage	Tubes, Insulation	04/03/2019	Success	Tubes have little to no wear
Device shall appropriately set insulation within tolerances for end conditions	Measure ends of tubes for tolerance after each isntallation	Full assembly, tubing and insulation	04/03/2019	Success	Insulation installation controlled by user
Device shall be compatible with tube diameters ranging from 3/8th - 1 inch	Test various tubing diameters using spring system for adjustment	Motor housing, tubing	02/27/2019	Sucess	Fine tune spring rates
Device shall not permanently warp tubing	Use tool as desiged, analyze tubing for degredation or damage	Full assembly, tubing, insulation	04/03/2019	Success	Insulation have little to no wear
Device shall not destroy insulation	Use tool as desiged, analyze insulation for degredation or damage	Full assembly, tubing, insulation	04/03/2019	Success	Insulation does not get damaged after initial installation (over several dozen installations it begins to show signs of wear)
The mechanism should be able to handle 50-100 a day, easily keeping up with the 5000 items a year.	Conduct fatigue analysis/FEA on components to predict service life of tool	Full assembly	04/03/2019	Success	Systems offer robust operation

Ergonomics- Green Performance-Red Versatility-Orange Cost Effectiveness -Blue

Pusher Design:

Appendix II is a DFMEA for the foam pusher device. The design criteria required that the solution (1) accommodate various tubing geometries and sizes; (2) produce defect-free, consistent results; (3) be user-friendly and ergonomic for the operators; and (4) reduce the current manufacturing times. The pusher design met all these criteria.

The design is scalable because the boat plug can be changed or modified to handle different size tubing. Also, due to the nature of the device, it will accommodate all tubing configurations, including three-dimensional bending. In testing, the device did not cause any damage to the foam insulation or tubing. There is a possibility that the foam could split down the seam, but this was never observed during testing. The device has proved to be simple to setup and operate (see section f of Concepts Considered, above). It also is more ergonomic than the current method of installation, because it requires far less manual force from the operator. Finally, the puller device can install the insulation in a fraction of the time required for the current manual process.

	Manual	Puller	Pusher
Set-up Time	0	37 sec	21 sec
Installation Time	1 min 20 sec	46 sec	18 sec
Effort (Out of 10)	10	5	4

Conclusions

In this project, we considered and tested several design concepts, but the paths we found to work most successfully were (1) the puller or tug design and (2) the pusher design. Overall, both systems indicate satisfactory proof-of-concepts. The lightweight tug allows for agility and ease of operation, pulling the the insulation as a truck would pull a trailer, around the bends in the pipe. However, further development would be required. The system is not entirely autonomous and some user intervention is required. The same is true for the foam pusher system. The puller system allows for a more ergonomic approach to installation, yet it still requires some operator assistance to guide the insulation along the tube, especially at sharp bends. Considering the drawbacks of the current, manual method either design would significantly improve the ergonomic conditions that the operator experiences during installation. User fatigue is greatly reduced and installation times are also decreased by a reasonable margin.

Recommendations

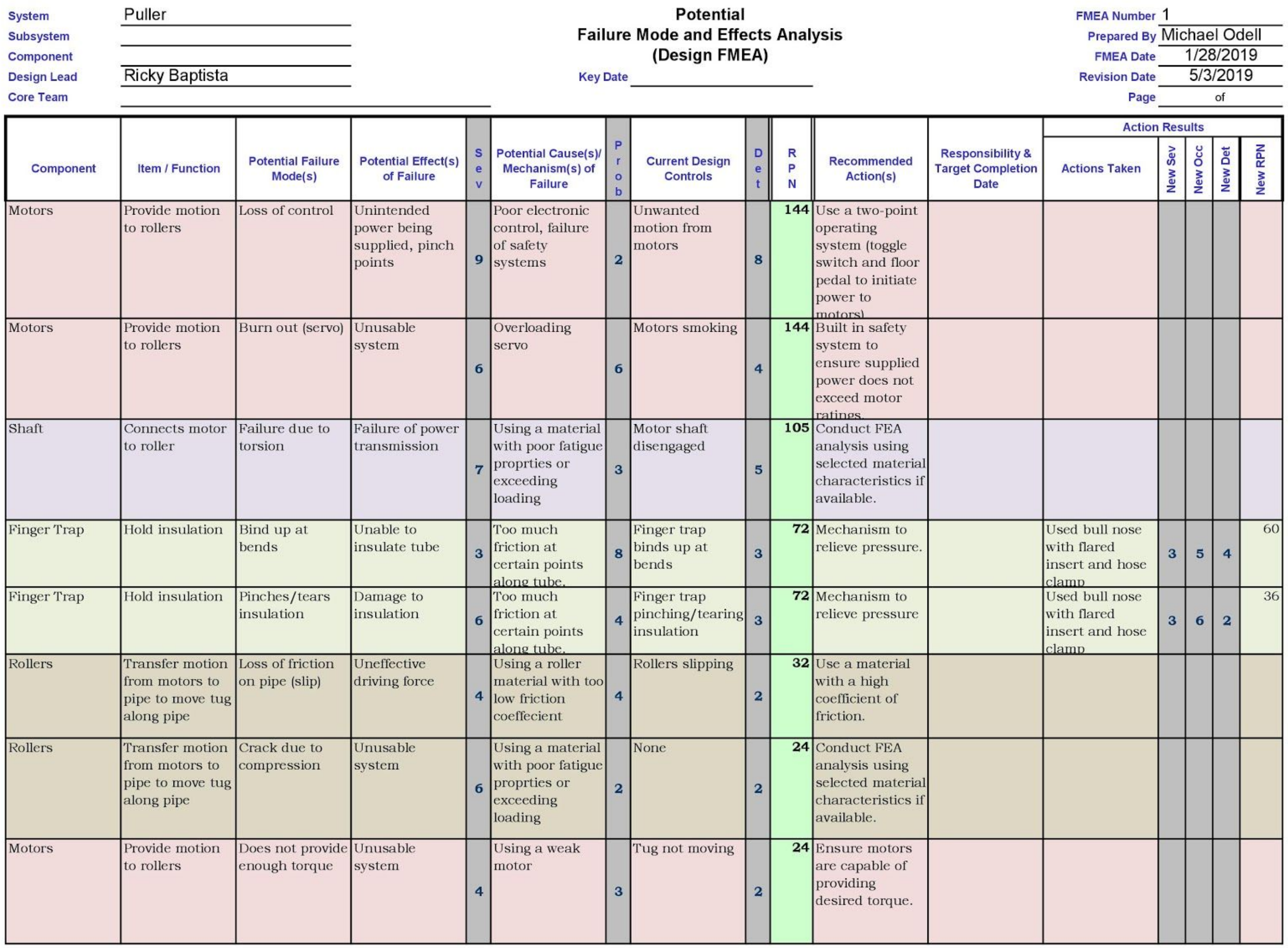
Based on the results, our recommendation would be to use the two mechanisms together, allowing the tug to navigate the pipe while the pusher feeds the insulation toward the tug. We believe the best approach would be to have an additional wireless controller, running the speed of the tug’s motors and the speed at which the pusher is being reeled in. This concept would give the user the capability to be at either end of the pipe inspecting the workings of the semi-autonomous device.

The pushing device should also be setup at a comfortable height for the operator. The winch of the device should be able to be operated with a controller that can remain near the operator. Both of these designs will improve the overall ergonomics of the system.

Other suggestions for improved designs are discussed in the System Integration section above.

Appendices

I. Puller DFMEA



System Puller
Subsystem
Component
Design Lead Ricky Baptista
Core Team

Potential
Failure Mode and Effects Analysis
(Design FMEA)

Key Date

FMEA Number 1
Prepared By Michael Odell
FMEA Date 1/28/2019
Revision Date 5/3/2019
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Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	New Sev	New Occ	New Det	New RPN
Motors	Provide motion to rollers	Loss of control	Unintended power being supplied, pinch points	9	Poor electronic control, failure of safety systems	2	Unwanted motion from motors	8	144	Use a two-point operating system (toggle switch and floor pedal to initiate power to motors)						
Motors	Provide motion to rollers	Burn out (servo)	Unusable system	6	Overloading servo	6	Motors smoking	4	144	Built in safety system to ensure supplied power does not exceed motor ratings						
Shaft	Connects motor to roller	Failure due to torsion	Failure of power transmission	7	Using a material with poor fatigue proprties or exceeding loading	3	Motor shaft disengaged	5	105	Conduct FEA analysis using selected material characteristics if available.						
Finger Trap	Hold insulation	Bind up at bends	Unable to insulate tube	3	Too much friction at certain points along tube.	8	Finger trap binds up at bends	3	72	Mechanism to relieve pressure.		Used bull nose with flared insert and hose clamp	3	5	4	60
Finger Trap	Hold insulation	Pinches/tears insulation	Damage to insulation	6	Too much friction at certain points along tube.	4	Finger trap pinching/tearing insulation	3	72	Mechanism to relieve pressure		Used bull nose with flared insert and hose clamp	3	6	2	36
Rollers	Transfer motion from motors to pipe to move tug along pipe	Loss of friction on pipe (slip)	Uneffective driving force	4	Using a roller material with too low friction coeffecient	4	Rollers slipping	2	32	Use a material with a high coefficient of friction.						
Rollers	Transfer motion from motors to pipe to move tug along pipe	Crack due to compression	Unusable system	6	Using a material with poor fatigue proprties or exceeding loading	2	None	2	24	Conduct FEA analysis using selected material characteristics if available.						
Motors	Provide motion to rollers	Does not provide enough torque	Unusable system	4	Using a weak motor	3	Tug not moving	2	24	Ensure motors are capable of providing desired torque.						

Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	New Sev	New Occ	New Det	New RPN
Tug Frame	Keep tug components together	Fracture due to fatigue	System will come apart	6	Using too thin of materials	2	Elastic bending of frame components	2	24	Run FEA simulation and understand fatigue characteristics.						
Finger Trap	Hold insulation	Loss of friction on insulation (slip)	Unusable system	4	Not enough grip from finger trap (cross sectional area).	3	Finger trap slipping	2	24	Augment finger trap with additional mechanisms to increase grip.						
Springs	Maintain contact between rollers and pipe	Does not provide proper amount of force	Improper force applied to rollers, insuffecient power delievery.	4	Choosing wrong springs	4	Spring does not provide proper amount of force	1	16	Select springs with appropriate spring constants.						
Finger Trap	Connect insulation to tug	Breaks due to tension	Damage to insulation	7	Too much friction at certain points along tube.	1	Finger trap material stretching	1	7	Mechanism to relieve pressure						
Springs	Maintain contact between rollers and pipe	Failure due to fatigue	Improper force applied to rollers, insuffecient power delievery.	3	Over-extension of springs, inappropriate max loading.	1	Spring does not return to normal shape	1	3	Select springs with appropriate spring constants.						